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GPS Sounding of the Ionosphere Onboard CHAMP

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ABSTRACT

Space based GPS measurements onboard Low Earth Orbiting (LEO) satellites provide a unique possibility for exploring the ionosphere on a global scale. Both the radio occultation measurements in the limb sounding mode and the navigation measurements using a zenith viewing GPS antenna provide the Total Electron Content (TEC) along numerous ray paths. TEC may effectively be used for reconstructing the spatial and temporal distribution of the electron density in the ionosphere and plasmasphere.

Reported are results obtained from radio occultation measurements on CHAMP which have provided more than 200,000 vertical electron density profiles so far. These observations contribute to a better understanding of the regular behaviour of the global ionosphere. Furthermore, the radio occultation measurements indicate irregular and/or wavelike structures in the ionosphere which may have severe impact on the functionality of radio systems.

A three-dimensional imaging of the electron density distribution near the CHAMP orbit plane between CHAMP and GPS orbit height is performed by using link related TEC data derived from dual frequency navigation measurements (zenith antenna) onboard CHAMP. This type of measurements provides a good measure of the interaction of the solar wind with the global Earth's atmosphere, thus providing a good opportunity for studying this interaction via the magnetosphere.

Key words: GPS, Ionosphere, Plasmasphere, Radio Occultation, CHAMP

1. INTRODUCTION

The capability of sounding the ionosphere by GPS measurements onboard Low Earth Orbiting (LEO) satellites has been demonstrated by several LEO satellite missions such as Microlab-1 with the GPS/MET experiment (e.g. Hajj and Romans, 1998, Schreiner et al., 1999), Ørstedt, and CHAMP (Jakowski et al., 2002, Garcia-Fernandez et al., 2003).

This paper deals with results of the ionosphere monitoring obtained by means of GPS measurements onboard the current geo-research satellite mission CHAMP (Reigber et al., 2000). The German CHAMP (CHAllenging Minisatellite Payload) satellite was successfully launched on 15 July 2000 into a near polar orbit (inclination 87°, altitude 450 km).The satellite is equipped with a dual frequency «Black Jack» GPS receiver which enables not only the use of GPS radio occultation measurements in the limb sounding mode, but also the analysis of the 0.1 Hz sampled navigation data.

The GPS data measured onboard CHAMP are received at the DLR Remote Sensing Data Center in Neustrelitz and subsequently processed at DLR by an operational data processing system (Wehrenpfennig et al., 2001).

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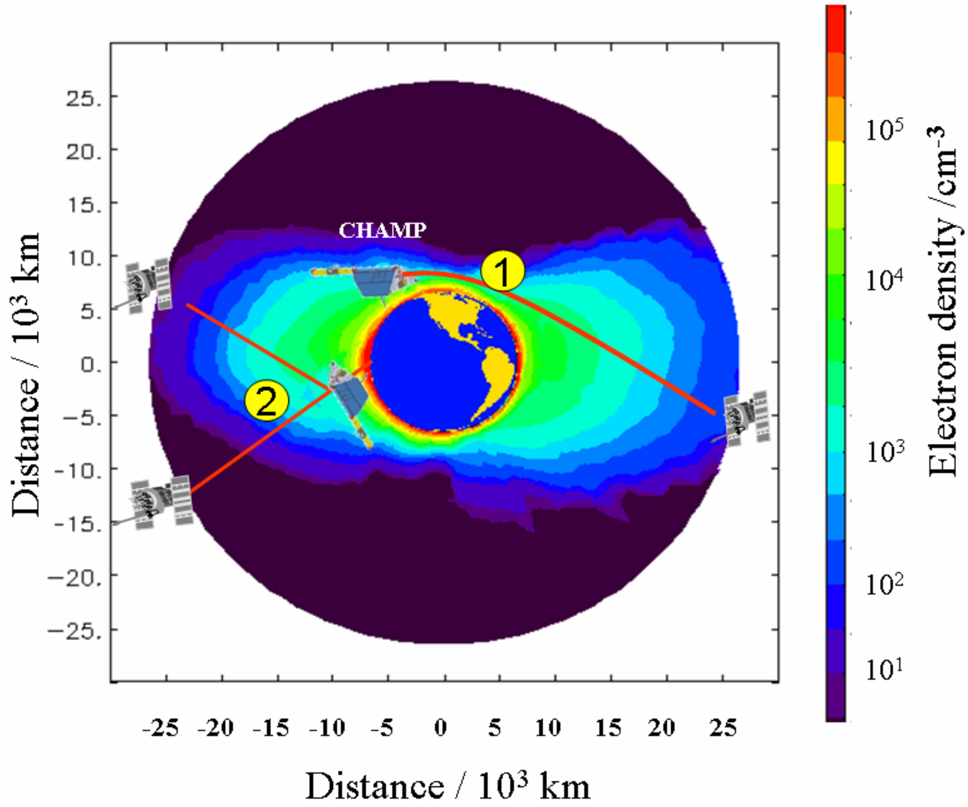

Fig. 1: Illustration of GPS measurement techniques used onboard CHAMP for sounding the ionosphere. (1): Ionospheric radio occultation (IRO) measurements in the limb sounding mode. (2): Use of 0.1 Hz sampled GPS navigation data from the zenith viewing antenna.

Fig. 1 illustrates the two different GPS measurement techniques which are used for ionosphere sounding. The Ionospheric Radio Occultation (IRO) experiment onboard CHAMP (1) provides up to 150 globally distributed vertical electron density profiles per day on a routine basis (Fig. 2). In addition to the IRO measurements, the 0.1 Hz sampled navigation data, measured with the zenith viewing antenna, can effectively be used for probing the topside ionosphere (Heise et al., 2002). Both, the IRO measurements as well as the topside data are operationally processed allowing fast access to global ionospheric information which can be used in near-real-time space weather monitoring.

2. GPS MEASUREMENT TECHNIQUES

Ionospheric Radio Occultation measurements

The GPS receiver onboard CHAMP measures carrier phases in the radio occultation or limb sounding mode starting at CHAMP orbit tangential heights down to the Earth surface with a sampling rate of 1 Hz. The measured GPS data are automatically checked and pre-processed by a highly flexible operational processing system (Wehrenpfennig et al., 2001). The processing flexibility is achieved thanks to the modular structure of the processing system in which the retrieval modules can be replaced and upgraded in the course of the CHAMP satellite mission. The original radio occultation measurements of the GPS satellites carried out with a sampling rate of 1 Hz include dual frequency L1/L2 carrier phase as well as code phase measurements.

Oppositely to the radio occultation sounding of the neutral atmosphere, the Ionospheric Radio Occultation (IRO) measurements can take benefit of the dispersive nature of the ionosphere. Thus, differential GPS phases derived from dual frequency GPS measurements can effectively be used for computing the integral of the electron density (TEC) along the ray path traversing the ionosphere.

The applied IRO retrieval method uses only the carrier phase measurements at L1 and L2 GPS frequencies which are described by the observation equation:

$$\phi = \rho + c(dt - dT) - d_I + d_{MP} + dq + dQ + N\lambda + \varepsilon \qquad (1)$$

where ρ is the true geometrical range between GPS satellite and receiver, c is the vacuum speed of light, dt and dT are the satellite and receiver clock errors, dI is the ionospheric delay along the ray path s, dMP is the multipath error, dq and dQ are the instrumental satellite and receiver biases, λ is the radio wave length, N is the phase ambiguity number (integer) and ε is the residual error. The space weather sensitive ionospheric propagation term dI is a function of the refraction index and can be written in a first order approximation by:

$$d_I = \frac{K}{f^2}\int_S^R n_e\,ds \qquad (2)$$

with K= 40.3 m^3s^{-2}.

Here the integral of the local electron density n_e along the ray path between satellite S and receiver R is the Total Electron Content already mentioned above. Ignoring the multipath term, instrumental delays and integer ambiguities N in eq. (1), the differential carrier phase $\Delta\phi = \phi_1 - \phi_2$ computed from carrier phases measured at L_1 and L_2 frequencies provides low noise TEC values. The method neglects dispersive ray path bending effects because these effects are small compared with the first-order-effects (Schreiner et al., 1999). The 1 Hz sampled relative TEC is measured along the radio occultation ray path which has a length in the order of 1000 km in the ionosphere and continuously approaches to the Earth surface measured by the tangential height.

The subsequent measurements form a set of equations which are successively solved from top to bottom, providing the electron density in the assumed spherical shells (Jakowski et al., 2002, 2004).

Since CHAMP has a rather low orbit height of less than 450 km, which decreases with mission time, the upper boundary condition is ill posed because of considerable ionization above the occultation entry. To overcome this upper boundary problem, a specific model assisted technique has been developed for the CHAMP IRO data analysis. The solution starts with the first measurement at the greatest tangential height by using an adaptive model for the topside ionosphere and plasmasphere above the CHAMP orbit height. This adaptive model consists of a Chapman layer whose topside part is extended by a slowly decaying exponential term with a fixed scale height value of 10,000 km. Key model parameters such as the plasma scale height at the upper boundary are determined in a few iterations in order to ensure a smooth transition between model values and measurements. It has been found that the crucial element for improving the solution of the upper boundary problem is the topside scale height (Stankov and Jakowski, 2006).

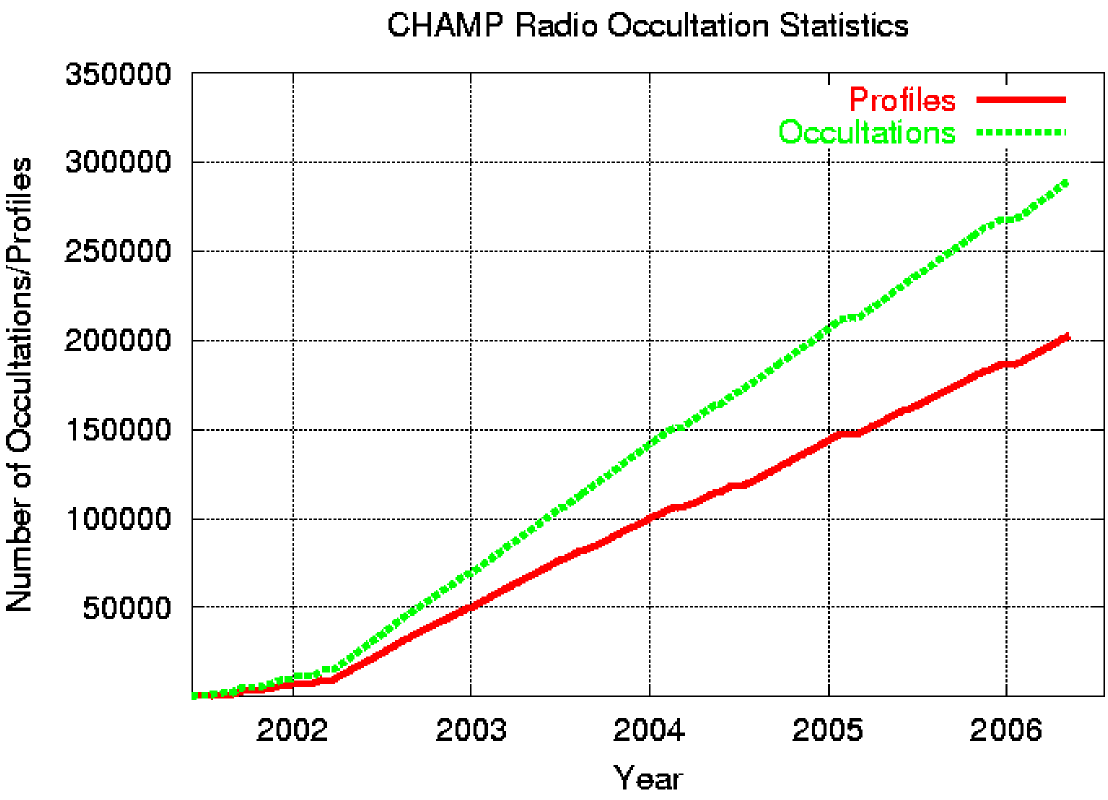

Fig. 2 Number of IRO measurements and retrieved vertical electron density profiles from 11 April 2001 until end of April 2006.

To fulfill space weather monitoring requirements, i.e. to come up with retrieval products within a latency of less than 3 hours as it is required by the traditional weather service, no further data are included in the retrieval procedure and for reasons of simplicity a spherically layered ionosphere is assumed (Abel inversion assumption). The retrieval can be improved if additional information, e.g. on horizontal gradients or local densities, as may be provided by TEC maps (http://www.kn.nz.dlr.de/swaci/). On average, from about 200 IRO measurements per day, about 150 electron density profiles (EDP) are successfully retrieved (Fig. 2) now adding up to the huge number of more than 200,000 profiles.

Because the processing system works automatically, the occurrence of outliers in the derived profiles cannot be avoided; however, the number of such outliers is less than 1%.

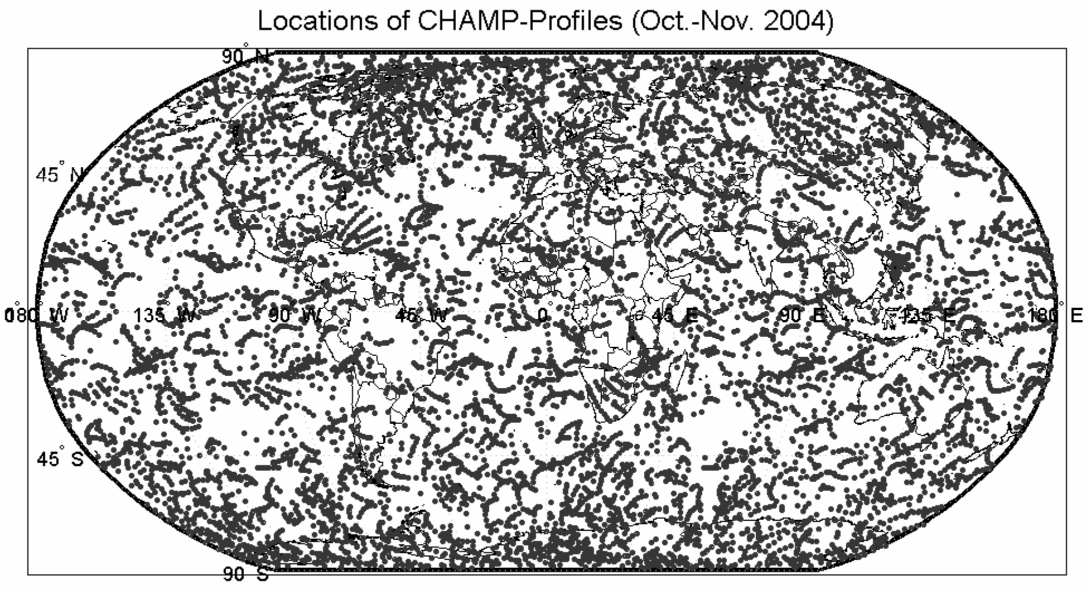

Fig. 3 Locations of retrieved radio occultation profiles during two months (October – November 2004).

As Fig. 3 shows, the measurements are uniformly distributed over the globe thus providing global information on the actual state of the ionosphere. Due to the nearly sun-synchronized orbit of CHAMP the local time sector is slowly shifting from day to day within a repetition period of 132 days (Fig. 4). Within this period the IRO measurements cover all local times. The local time constraint of IRO measurements is less restricted at high latitudes, indicated by the occurrence of measurements between the pronounced LT-bands in Fig. 4.

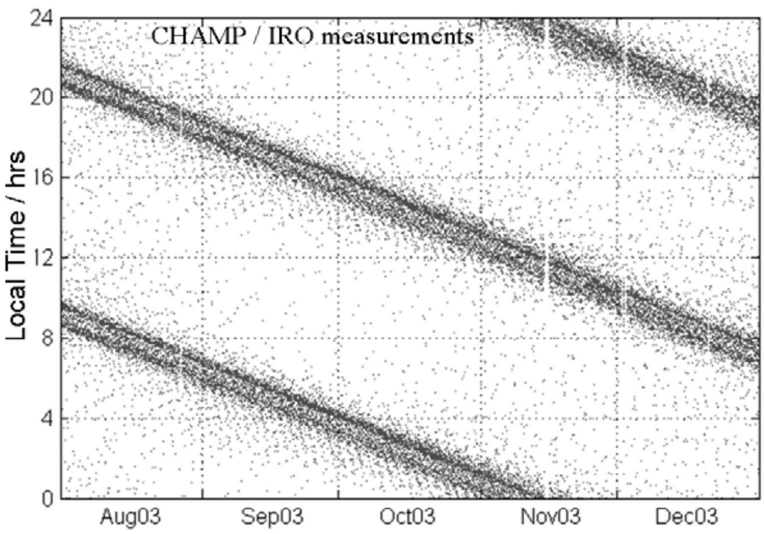

Fig. 4 Local time sector of ionospheric radio occultation measurements during months August – December 2003.

A typical product sample obtained after automatic retrieval of IRO measurements onboard CHAMP at 48.93 °S; 128.76°E over the Indian Ocean around local noon is shown in Fig. 5. The corresponding data files can be downloaded via the DLR space weather service (http://www.kn.nz.dlr.de/swaci/). The quality label of the data products (0 - 9) provides a rough estimation of the reliability of the retrieval (0 marks the highest level). All analyses presented here were made with the quality label 0 or 1.

To estimate the quality of the derived electron density profiles, a number of validation efforts were undertaken including ionosonde data from the European vertical sounding stations Juliusruh (54.6°N; 13.4°E), Athens (38.0°N; 23.5°E), Rome (41.9°N; 12.5°E), Tortosa (40.8°N; 0.5°E) and Dourbes (50.1°N; 4.6°E) (Jakowski et al., 2005a).

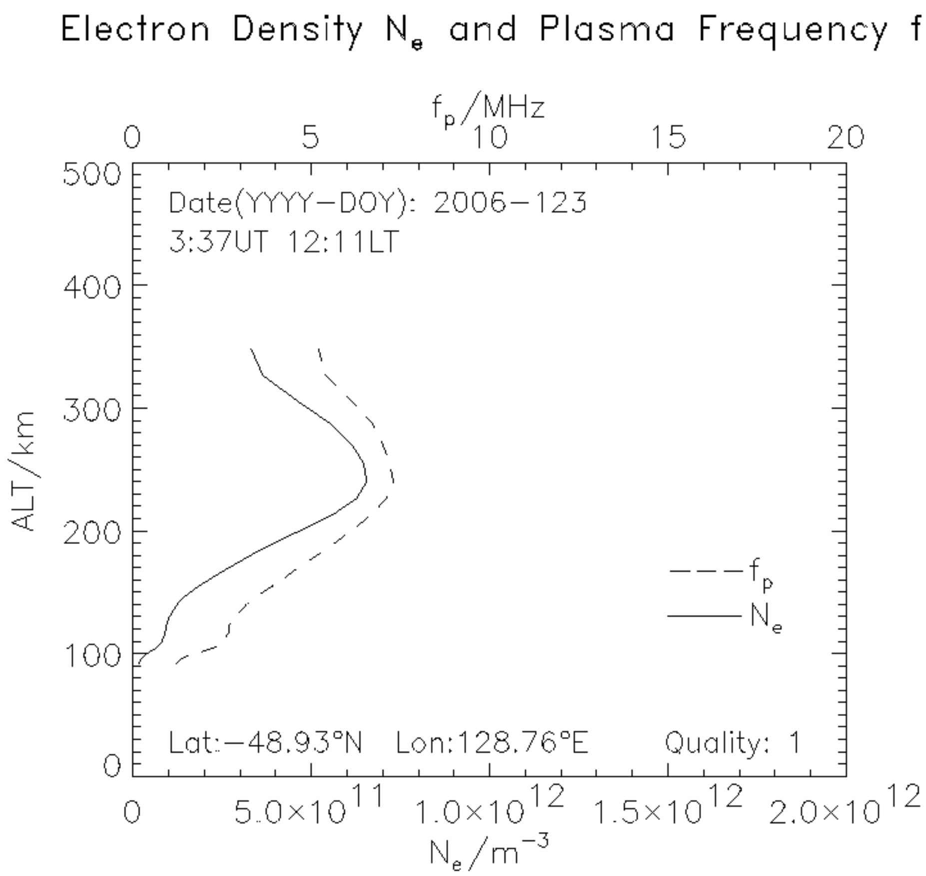

Fig. 5 Data product sample showing the IRO retrieval of the SWACI service.

To give an impression of the achieved accuracy, the validation with ionograms of the Juliusruh ionosonde station has indicated a bias of up to 0.5 MHz and a RMS error of about

1 MHz in the plasma frequency (Jakowski et al., 2004, 2005a). More validation work is required in particular for low latitude data.

Principally, it has to be stated that the IRO derived electron density profiles provide a unique measure describing the mean vertical electron density structure in comparably large areas with characteristic lengths of about 1000 km.

Topside ionosphere / plasmasphere measurements

Whereas the IRO retrieval technique can work with non-calibrated carrier phase derived TEC data (Jakowski et al. 2002), the topside assimilation reconstruction technique requires calibrated TEC data along the numerous radio links between the GPS satellites and the topside GPS antenna onboard CHAMP (Fig. 6). Depending on the relative CHAMP-GPS satellite constellation the data coverage changes permanently. Usually the data are not homogeneously distributed as Fig. 6 demonstrates. To overcome this problem, the reconstruction is made via data assimilation into a reliable background electron density model.

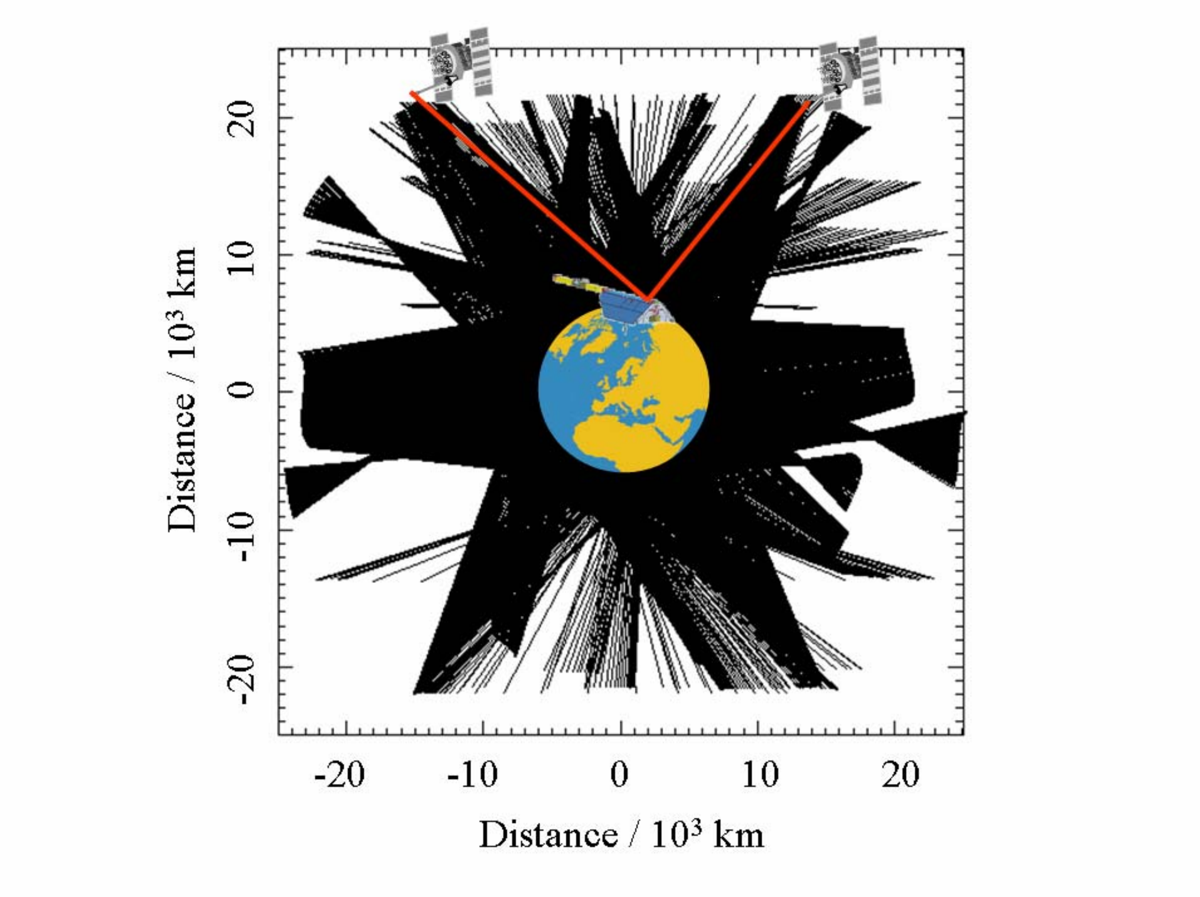

Fig. 6: Illustration of the topside radio link distribution in the CHAMP orbit plane to the visible GPS satellites during one satellite revolution.

Before starting the reconstruction, the corresponding satellite and receiver biases (eq. 1) have to be estimated properly before the assimilation procedure can be started.

During the pre-processing stage, detected outliers are being removed and cycle slips are corrected. For reconstructing the topside ionosphere/plasmasphere electron density the Parameterized Ionospheric Model PIM (Daniell et al., 1995) has been selected to act as the background model. After calibrating the differential phases, the absolute TEC data are assimilated into the PIM model by a method described by Heise et al. (2002). The assimilation results provide a 3D reconstruction of the electron density for each CHAMP revolution in the vicinity of the CHAMP orbit plane.

Validation of the derived electron density distribution was made with in situ plasma density measurements of the Planar Langmuir Probe installed onboard CHAMP and incoherent scatter measurements at different sites.

As shown by Heise et al., 2002, the assimilation results have no significant bias and agree with the Langmuir Probe in situ data with a standard deviation of $2x10^{11}m^{-3}$. Reasonable agreement was also found with topside profiles deduced from incoherent scatter measurements.

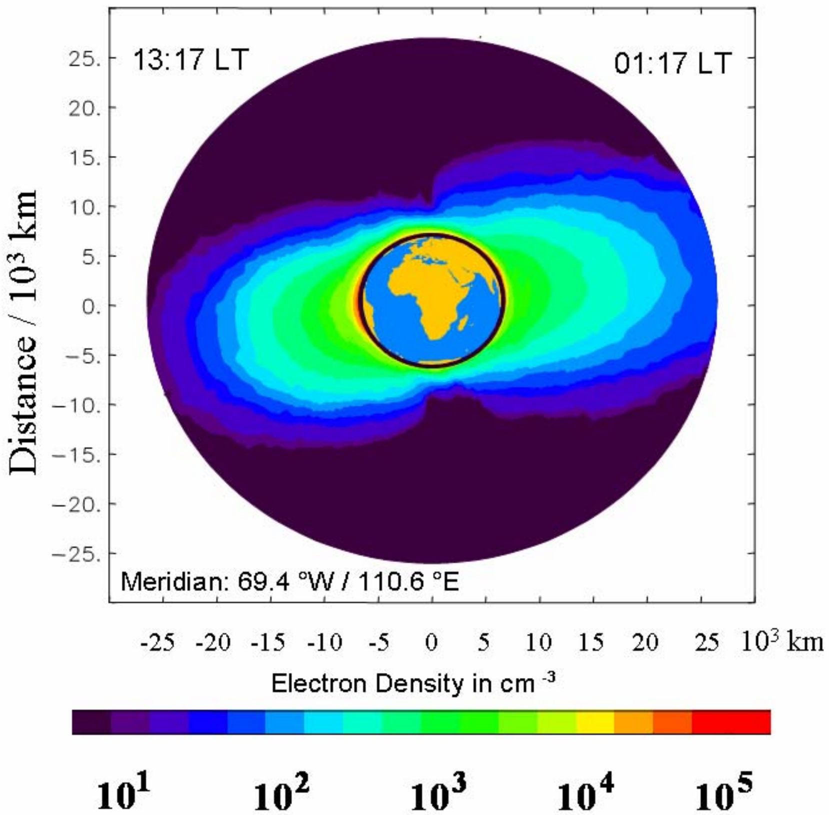

Fig. 7: Reconstruction of the electron density distribution of the topside ionosphere based on GPS data received onboard CHAMP. The reconstruction is based on medians obtained for 21:00 UT over 10 consecutive days in August 2005. Thus, the right side shows the ionosphere/plasmasphere shortly after midnight whereas the left side represents ionosphere shortly after noon.

As Fig. 7 demonstrates, the global view on the Earth's plasma environment enables the study of magnetospheric-ionospheric coupling processes. Here, the compression of the plasmasphere at the day-side and the enlarged extension of the plasmasphere at the night-side are clearly visible. Thus, it becomes evident that this type of space based GPS measurements can provide essential contributions to a space weather monitoring of the ionosphere.

3. OBSERVATION RESULTS AND DISCUSSION

Global data coverage and the huge amount of more than 200000 electron density profiles allow efficiently studying global large scale ionospheric processes. Because the first data were obtained in 2001 under rather high solar activity conditions, the observations enable conclusions about the solar activity dependence of key ionospheric parameters.

Since the ionospheric ionization is essentially produced by solar radiation of wavelengths shorter than 130 nm, there is a strong solar cycle variation of the ionospheric peak density and other parameters related to the structure of the thermosphere/ionosphere. The solar activity control of the ionization level, well-known from TEC-measurements (e.g. Jakowski et al., 1991) is clearly visible in the level of the peak electron density derived from IRO measurements onboard CHAMP (Fig. 8).

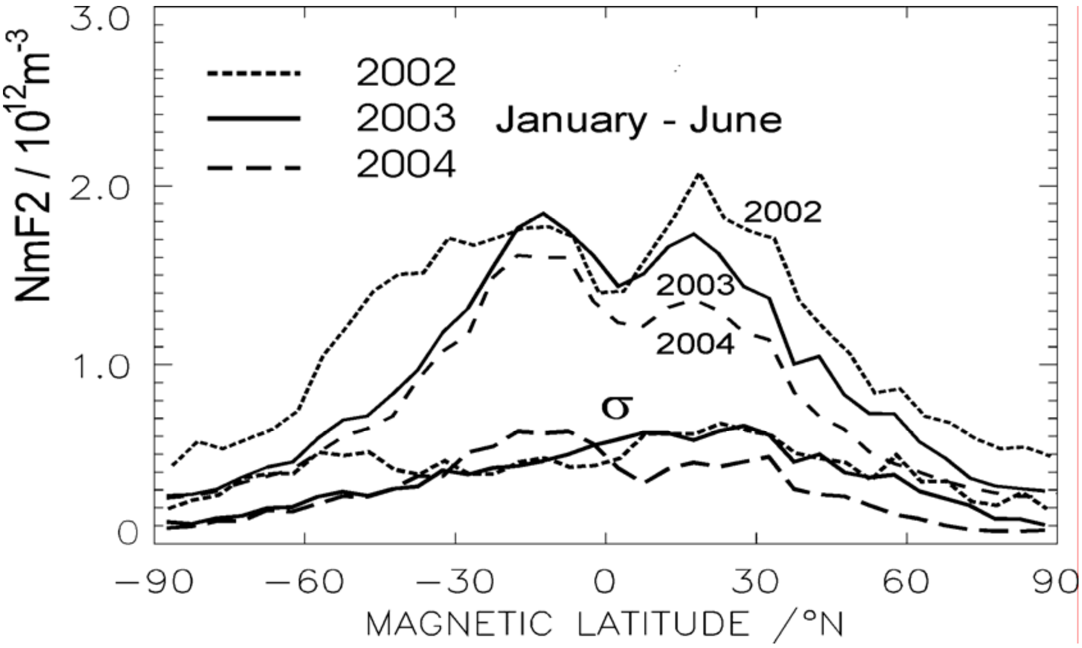

Fig. 8: Latitudinal dependency of the day-time (08:00-16:00 LT) F2 layer peak electron density NmF2 as seen in the CHAMP IRO data at three years 2002-2004 for all longitudes. The corresponding standard deviation σ is given at the bottom of the figure.

Fig. 8 shows that the F2 layer ionization reduces up to 30 % at daytime from 2002 to 2004, when the average solar radio flux F10.7 cm decreases from about 180 down to 107 by about 40%.

It is obvious that the solar radiation induced photo ionization of the Earth's atmosphere depends on the incidence angle of the irradiation. Thus, the general behavior of the latitudinal variation of the total ionization in Figs. 8 and 9 can easily be explained.

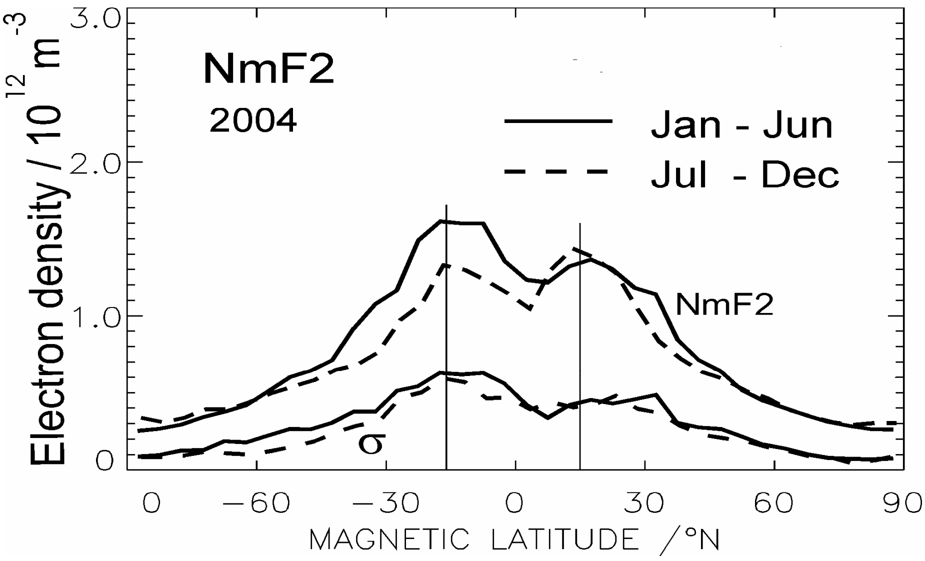

Fig. 9: Latitudinal dependence of the peak electron density NmF2 summarizing all measurements obtained in 2004 in the first and second half years at daytime (08:00 -16:00 LT) for all longitudes. The crest locations are marked at about ±15° magnetic latitude and the standard deviation σ is given at the bottom of the figure.

However, since the plasma motion is strongly influenced by magnetic und electric fields, the latitudinal dependence of the peak electron density demonstrates a more complex relationship with the solar activity. The well-known equatorial anomaly, characterized by enhanced ionization at about 15° at both sides of the geomagnetic equator is due to electric fields generated near the geomagnetic equator. The ionospheric plasma is uplifted at the geomagnetic equator via **E** x **B** drift and, while returning back, enhances the topside electron density at both sides of the geomagnetic equator, thus forming the so-called equatorial crest.

This can nicely be seen also in the latitudinal dependence of the day-time peak density height hmF2 in Fig. 9 where hmF2 reaches an absolute maximum of about 375 km near the geomagnetic equator. The northward shift of the maximum is due to seasonal effects because the northern summer hemisphere is stronger heated than the southern winter hemisphere. If high latitudes > 65° are excluded, the general behavior indicates positive linear trends directed to the warmer summer hemisphere for hmF2, the scale height Hs and the bottomside equivalent slab thickness τb as well. The following gradients may roughly be estimated:

The peak density height hmF2 and the scale height Hs grow up from winter to summer by about 140 m/deg whereas the bottomside slab thickness grows up in the average by a rate of approximately 410 m /deg.

Enhanced thermospheric heating during summer leads to an expansion of the thermospheric density distribution resulting in an increased peak density height and increased shape parameters slab thickness and topside scale height of the electron density profiles. This explanation is also confirmed when looking to the solar cycle dependence of these parameters showing biggest values at high solar activity conditions.

Compared with 2001, the peak density height decreases in average by about 75 km throughout all latitudes within in 2004.

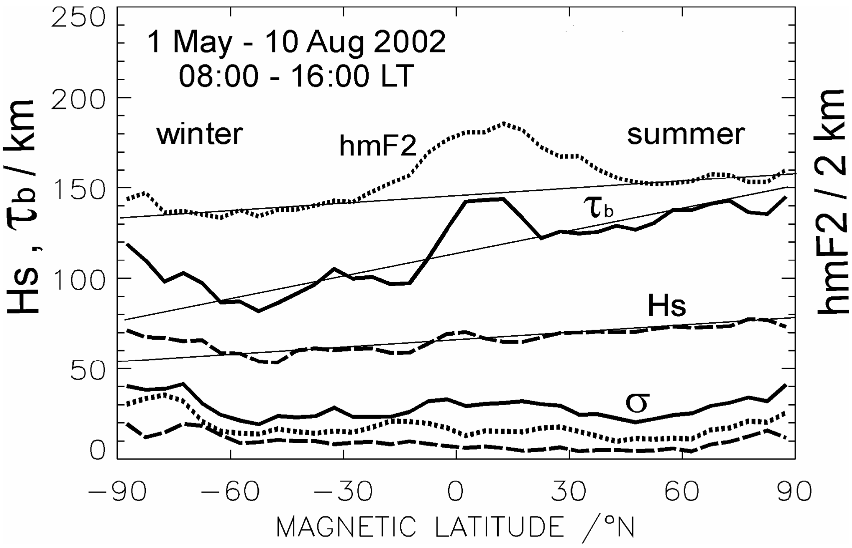

Fig. 10: Latitudinal dependence of the peak density height hmF2 and shape parameters such as bottomside slab thickness τ_b and the topside scale height Hs at 425 km height measured at daytime in Northern summer. The corresponding standard deviation σ of all three parameters is given at the bottom of the figure.

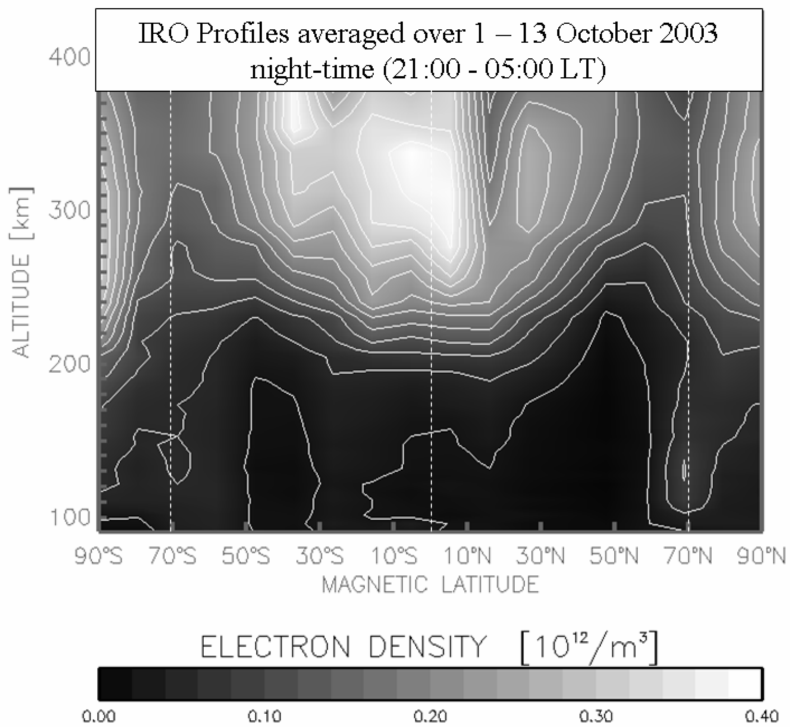

Fig. 11: Imaging of the average vertical ionization structure constructed from all IRO profiles obtained during the first 13 days in October 2003 between 21:00 and 05:00 LT. Marked are geomagnetic latitudes at 70° and at 0°.

The observed high latitude enhancement of all three parameters at the winter hemisphere is probably due to thermospheric heating as a consequence of particle precipitation and the action of the auroral electrojet. During night-time the polar ionosphere is separated from the mid-latitude ionosphere by the so-called trough region which is characterized by very low electron densities. As Fig. 11 shows, IRO profiles reflect this phenomenon very well in their average plot.

Although the limb sounding mode principally leads to a strong averaging of the observational data, the IRO measurements document the existence of numerous irregularities in the ionosphere (Tsybulya and Jakowski, 2005).

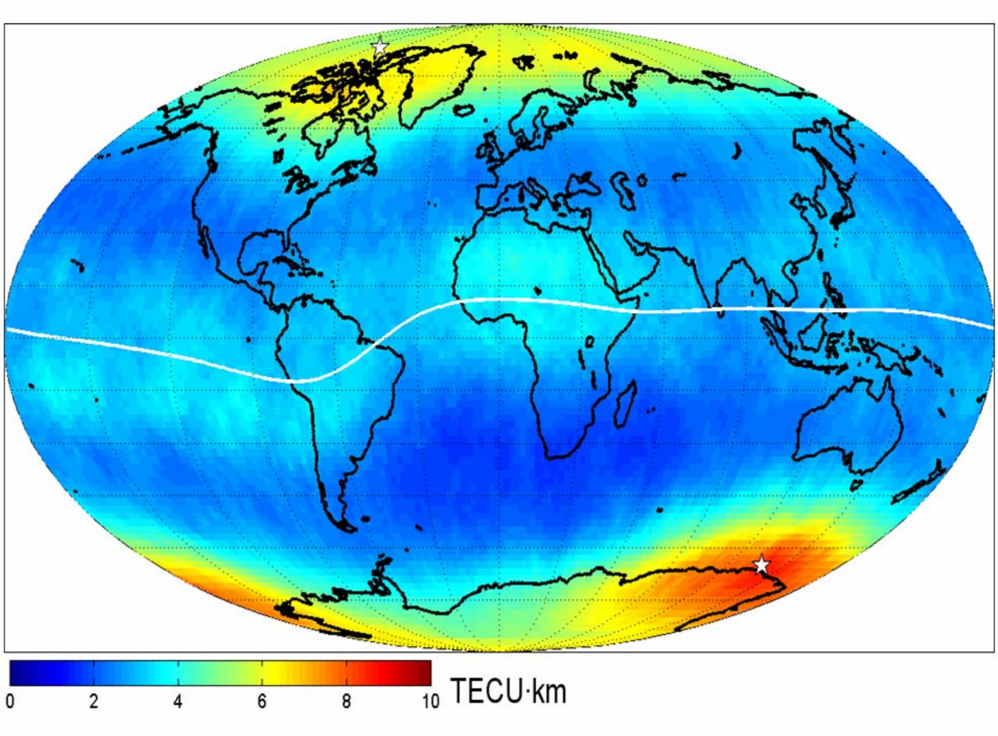

Fig. 12: Global distribution of the occurrence of ionospheric irregularities (characteristic scale length about 15-30 km) detected in IRO CHAMP data from March 2002 – February 2006. Geomagnetic poles are marked by asterisks, the magnetic equator by a full line.

As Fig. 12 shows, the perturbation level is clearly pronounced in the Polar Regions, in particular around the geomagnetic poles. Although upward propagation of atmospheric gravity waves cannot be excluded it is assumed that these perturbations are more likely related to thermospheric/ionospheric interaction processes (Tsybulya and Jakowski, 2005). Furthermore, the IRO data from CHAMP have clearly shown that the TID activity is more pronounced in winter nights.

Severe space weather events modify the magnetosphere/ionosphere and thermosphere systems at quite different spatial and temporal scales. The GNSS measurements onboard CHAMP are well suited to monitor in particular large scale effects in time and space. Thus, storm induced changes of the ionospheric plasma developing at characteristic times of a few days and scale lengths of up to several thousand kilometers can be monitored effectively by analyzing the topside electron density reconstructions (e.g. Jakowski et al., 2005b).

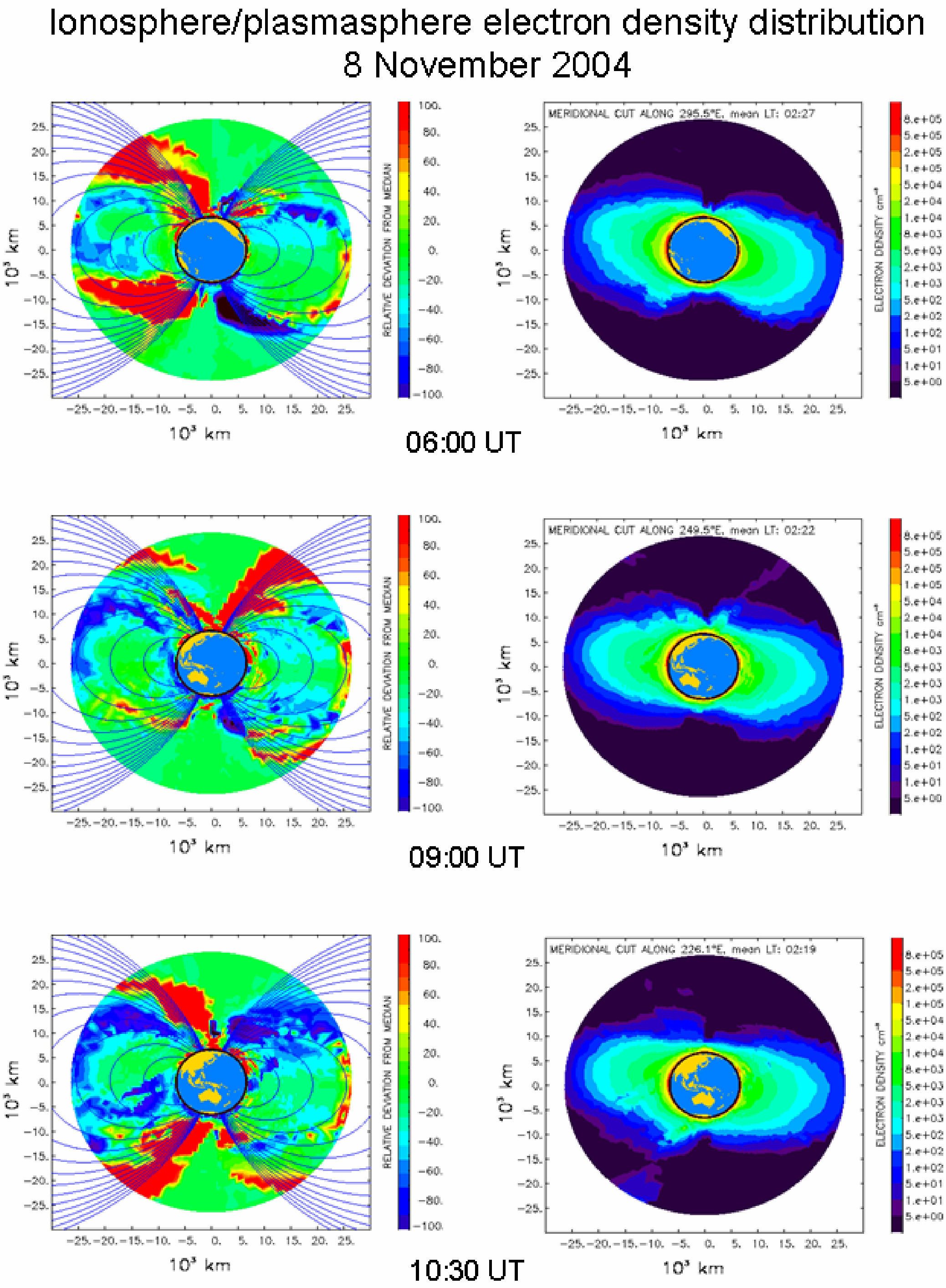

Fig. 13: Comparison of subsequent reconstructions of the 3D electron density structure during the ionospheric storm on 8 November 2004 in comparison with percentage deviations from corresponding medians ($\Delta n_e / n_e \cdot 100\%$).

During the storm on 7/8 November 2004 the electron density reconstructions in the CHAMP orbit plane indicate strong irregular behavior in particular close to the plasma pause region. The time period covered by the plots in Fig. 13 corresponds with the time of D_{st} minimum value at 08:00 UT on November 8, 2004. Strong enhancements of the electron density are seen at high latitudes indicating plasma upflow in the auroral ionosphere at both hemispheres. Whereas such a plasma flow is more pronounced at the day-time polar zones at 6:00 UT and 10:30 UT, the outflow is focused at the northern pole around 9:00 UT. We are aware of the fact that the reconstructions are derived from a limited TEC data base and simplified assumptions. Nevertheless, the analysis of several storms indicates strong enhancements and also suppressions of the electron density. To avoid misinterpretation, we have counted only strong perturbation induced electron density deviations which exceed corresponding median values by 50% or are less than half of the median. The result, obtained for the storm on 20/21 November 2003, is shown in Fig. 14.

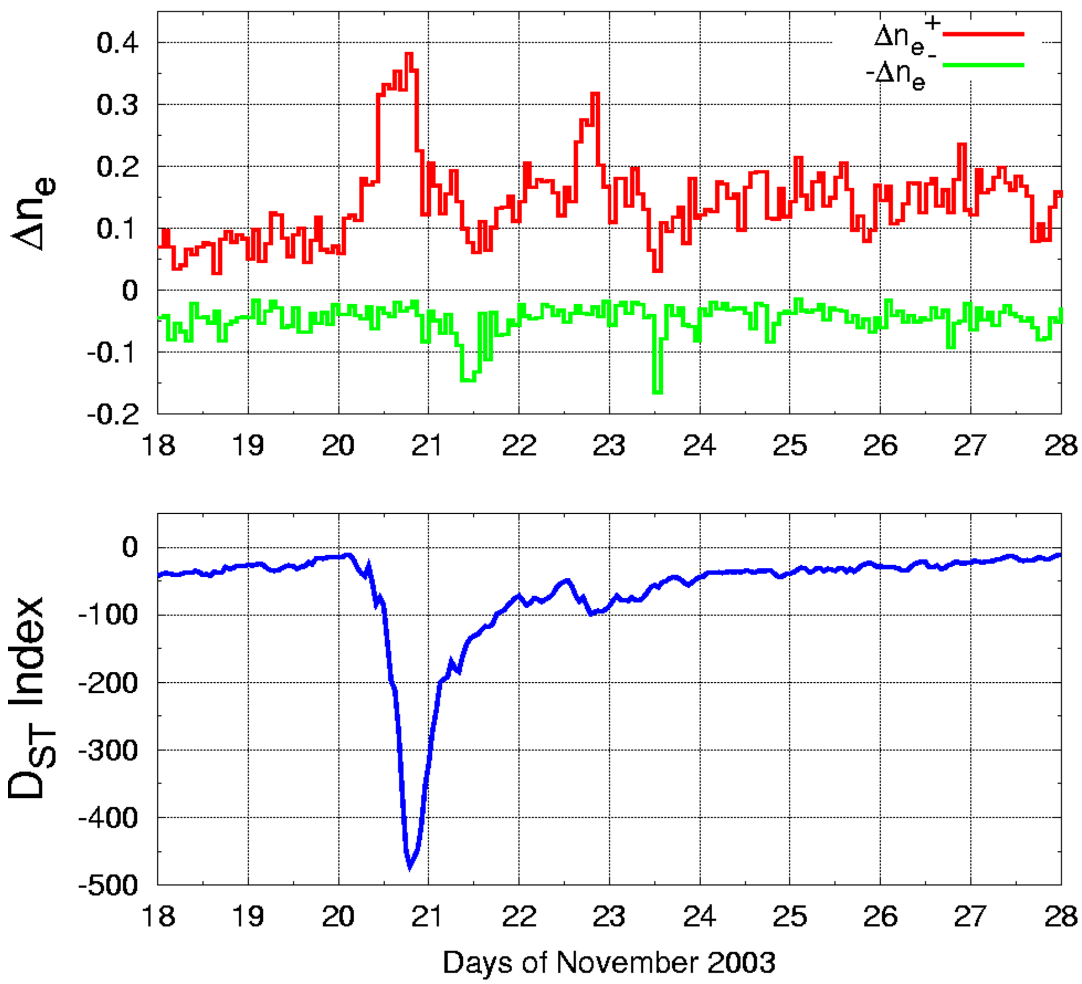

Fig. 14: Comparison of positive and negative deviation counts of the electron density values that exceed a certain threshold value ($|\Delta n_e| > 50\%$) from corresponding means with the geomagnetic D_{st} index (http://swdcdb.kugi.kyoto-u.ac.jp/dstdir/).

It is interesting to see that the topside ionosphere/plasmasphere considerably blows up in the growing phase of the storm whereas it reduces in the recovery phase. This behavior even repeats during a sub-storm starting around 12 UT on 22 November confirming the conclusion. Although we are aware of some remaining constraints of the reconstruction technique, e.g. due to incomplete data coverage, we believe that the basic observation results are correct.

Conclusions on the principal behavior of the plasmaspheric dynamics during geomagnetic storms are more reliable if several storms are superposed. Corresponding studies are planned.

4. SUMMARY AND CONCLUSIONS

The large data base of IRO-derived electron density profiles and reconstructions of the topside ionosphere/plasmasphere electron density distribution is a valuable data source for the international scientific community. The obtained space based GPS measurements contribute to a better understanding of solar-terrestrial relationships, and are valuable for developing and improving global ionospheric models. Due to the near-real-time processing of the satellite data the CHAMP satellite provides operational space weather information. To make this information available as fast as possible, DLR has established a permanent space weather service under http://www.kn.nz.dlr.de/swaci which provides both ground as well as space based GPS measurements and corresponding ionospheric data products.

To fulfill the user requirements for a space weather service, robust and sufficiently accurate retrieval techniques are needed. The CHAMP automatic processing system is able to provide ionospheric data products within 3 hours after scientific data dump in Neustrelitz.

Validation of IRO data has revealed that the F2 layer peak electron density f0F2 and the corresponding height hmF2 agree quite well within 20% deviation.

The standard deviation of vertical sounding derived electron density profiles is in the order of 1 MHz plasma frequency throughout the entire IRO profile.

Although the good agreement between IRO measurement data and other types of independent measurements has proved the quality of the IRO retrieval technique, the validation process is planned to be continued. Further validation is also required for the topside reconstruction data which we have shown to image large scale structures of severe ionospheric perturbations.

To enhance the resolution of 3D reconstruction of the global ionospheric electron density distribution, space based GNSS sounding should be combined with ground based GNSS measurements.

The launch of new occultation satellites such as COSMIC, SWARM or TerraSAR-X offers great promise for modeling and monitoring the electron concentration in the near-Earth-space for scientific studies and continuous space weather monitoring.

Acknowledgements

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